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Injury and Yield Response of Cotton to Chronic Doses of Ozone and Sulfur Dioxide

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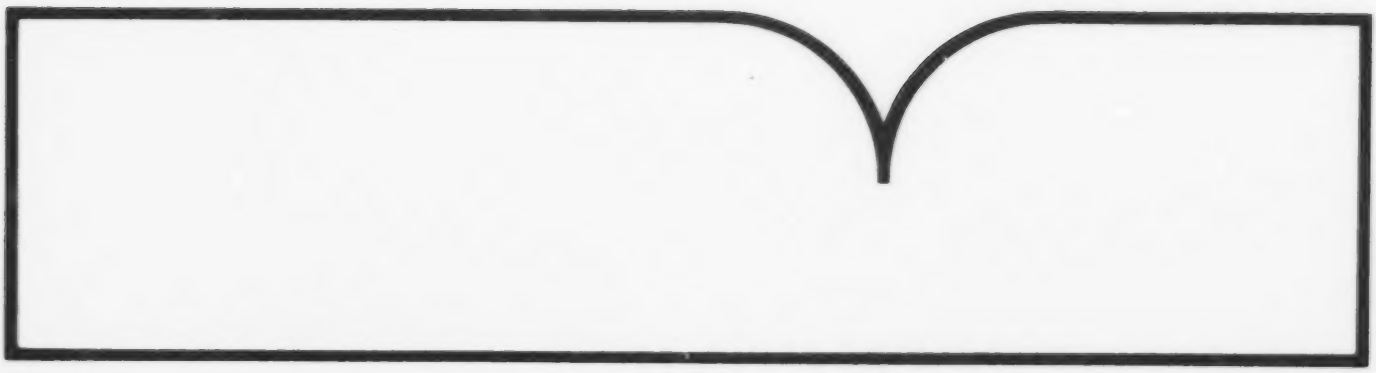

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16. ABSTRACT

Knowledge of relationships between chronic doses of O_3 and crop yield is required to set air quality standards that protect agricultural interests and to determine the need to develop resistant cultivars of sensitive species. Open-top field chamber studies have provided some information of this type for a few crop species including one western cultivar of cotton. Our objectives were to measure relationships between chronic doses of O_3 and yield of an eastern cotton cultivar and to determine whether these relationships could be affected by chronic doses of SO_2. 'Stoneville 213' was exposed in open-top field chambers to five doses O_3 and four doses of SO_2 singly, and in all possible combinations. Exposures began when first foliar leaves were expanding and continued until final harvest. Stoneville 213 was sensitive to O_3-induced yield decrease and regression analyses provided models describing this relationship. Compared to cotton yield in charcoal-filtered-air chambers, the measured decrease of cotton yield at levels of O_3 that occurred during the 1982 season at Raleigh, NC was 11%. Doses of SO_3 at levels greater than those occurring regionally did not significantly change cotton response to O_3.

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JOURNAL ARTICLE

Injury and Yield Response of Cotton to Chronic Doses of Ozone and Sulfur Dioxide[1]

ALLEN S. HEAGLE, W. W. HECK, V. M. LESSER, J. O. RAWLINGS, AND F. L. MOWRY[2]

ABSTRACT

Knowledge of relationships between chronic doses of O_3 and crop yield is required to set air quality standards that protect agricultural interests and to determine the need to develop resistant cultivars of sensitive species. Open-top field chamber studies have provided some information of this type for a few crop species including one western cultivar of cotton (*Gossypium hirsutum* L.). Our objectives were to measure relationships between chronic doses of O_3 and yield of an eastern cotton cultivar and to determine whether these relationships could be affected by chronic doses of SO_2. 'Stoneville 213' was exposed in open-top field chambers to five doses of O_3 (seasonal 7 h d^{-1} means from 0.026–0.104 $\mu L\ L^{-1}$) and four doses of SO_2 (seasonal 4 h d^{-1} means from 0.00–0.35 $\mu L\ L^{-1}$), singly, and in all possible combinations. Exposures began when first foliar leaves were expanding and continued until final harvest. Stoneville 213 was sensitive to O_3-induced yield decrease and regression analyses provided models describing this relationship. Compared to cotton yield in charcoal-filtered-air chambers, the measured decrease of cotton yield at levels of O_3 that occurred during the 1982 season at Raleigh, NC was 11%. Doses of SO_2 at levels greater than those occurring regionally did not significantly affect cotton and did not significantly change cotton response to O_3.

Additional Index Words: Gossypium hirsutum, **air-pollution stress, seed and fiber properties.**

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Ozone in photochemical oxidant air pollution is estimated to cause from $3 to 4 billion in production losses annually to major agronomic crops in the USA (8, 12, 13). These estimates were based on field experiments that established O_3 dose-yield response relationships. Generally, only one or two cultivars per species have been tested.

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[2]Plant Pathologist, USDA-ARS, Dep. of Plant Pathology, Plant Physiologist, USDA-ARS, Dep. of Botany; Statistician, Dep. of Statistics; Professor of Statistics, Dep. of Statistics; and Micrometeorologist, Dep. of Botany; North Carolina State Univ., Raleigh, NC 27695.

The cotton crop (*Gossypium* spp.) in the USA has an annual farm value of about 3.5 billion dollars (19). Present evidence suggest that cotton is sensitive to O_3 at levels that occur regularly where cotton is grown (1, 2, 14). Yield of cotton grown in chambers where O_3 was partially removed by charcoal filtration (CF) has been compared with yield of cotton grown in chambers receiving nonfiltered air (NF). In greenhouses at Beltsville, MD, yields of 'Acala SJ-1', 'Stoneville 213', and 'Deltapine Smooth Leaf' were 12, 14, and 31% less, respectively, in NF air than in CF air (14). At Parlier, CA, yield of 'Acala SJ-2' in field chambers with partial air filtration (1/3 CF), NF air, or NF air with O_3 added (to achieve twice the NF concentration) was 5, 15, and 33% less, respectively, than that in CF air (1). These studies showed the need to determine the relationship between O_3 doses and cotton yield.

Experiments in open-top field chambers at Shafter, CA in 1981 and 1982 (18) provided data on the effects of O_3 doses on yield of 'Acala SJ-2' cotton. However, field data do not exist for cotton cultivars grown in the remainder of the cotton belt. The open-top chambers used at Shafter, CA (18) were each equipped with a truncated cone (frustum) (4, 15) that decreased ingress of ambient air into the chambers during windy periods. The effects of frusta on plant growth and plant response to O_3 in open-top chambers has not been determined.

In most areas, SO_2 levels are probably too low to cause significant foliar injury and decreased yield but small concentrations of SO_2 in combination with ambient levels of O_3 can cause greater than additive amounts of foliar injury (17). For field-grown soybeans [*Glycine max* (L.) Merr.], there were no significant interactions between O_3 and SO_2 for injury and yield responses (7, 9), but there are no reports of similar field studies for other crops.

This study had the following objectives: (i) to measure the effects of chronic doses of O_3 and SO_2 on injury, growth, and yield of an eastern cotton cultivar grown in the field; (ii) to determine whether the presence of either pollutant would change the response of cotton plants to exposure to the other; and (iii) to compare cotton growth and yield response to O_3 in open-top chambers with and without frusta.

MATERIALS AND METHODS

The experiment was performed during 1982 in a field located 8-km south of Raleigh, NC. The soil was approximately 30 cm of Norfolk loamy sand (fine-loamy, siliceous, thermic, Typic Paleudults) that had been placed over approximately 15 cm of Appling sandy loam (clayey, kaolinitic, thermic, Typic Hapludults) in 1980. The field was fertilized according to soil-test recommendations and trifluralin (α,α,α-trifluoro-2,6-dinitro-*N*,*N*-dipropyl-*p*-toluidine) was applied at the rate of 1.2 L ha^{-1} before planting. Fluometuron [1,1-dimethyl-3(α,α,α-trifluoro-*m*-tolyl)urea] was applied at the rate of 1.4 kg ha^{-1} at planting.

Cotton, Stoneville 213, was planted on 20 May with a two-row planter on 1-m centers. Peak plant emergence occurred on 24 May and 3-m^2 plots were selected based on plant stand and soil uniformity. On 31 May, frames of open-top chambers (6) were installed on 25 treatment plots that contained two rows of cotton apiece. Two 2-m sections of row, one each located 1.2-m east and 1.2-m west of the fan box of each chamber, were used as a companion plot for each treatment plot. Cultural practices were similar for all plots. Plants were thinned on 11 June to three to four plants per 30 cm of row resulting in 9 to 11 plants m^{-1} of row. Soil tensiometers (Irrometer Co., Riverside, CA) installed adjacent to one row in each plot at depths of 30 and 45 cm were used to determine irrigation needs. The seasonal climate was close to average with 47 cm of rain. Depending on the plot, a total of 16.7 to 19.5 cm of irrigation water was applied in increments of 1.1 to 2.5 cm on 10 to 11 d between 14 July and 20 September. Insects and mites were controlled with applications of dimethoate [*O,O*-dimethyl *S*-(methylcarbamoylmethyl) phosphorodithioate], dicofol (4,4'-dichloro-α-trichloro-methylbenzhydrol), permethrin (*m*-phenoxybenzyl *cis, trans*-(+)-3-(2,2-dichloro-vinyl)-2,2-dimethyl-cyclopropanecarboxylate), and cyhexatin (tricyclohexylhydroxy-stannane).

Pollutant Treatment

On 7 June, clear polyvinyl chloride-film panels were installed to enclose the chambers. Chamber fans were run daily from 0600 to 2200 h EDT for the remaining season. The experimental treatments consisted of one replicate of a 5 × 4 factorial set of O_3 × SO_2 treatments plus a repeat of the five O_3 treatments at the low level of SO_2 with the exposure chambers modified to include a frustum. The 20 treatments in chambers without frusta, consisting of all possible combinations of five levels of O_3 and four levels of SO_2, and the five O_3 treatments in chambers with frusta were randomly assigned to the plots. Methods for dispensing and monitoring have been described previously (9, 11).

The five levels of O_3 consisted of charcoal-filtered air (CF), and four nonfiltered-air (NF) treatments (particle filter only) with different levels of O_3 added. The fluctuating O_3 concentrations in ambient air were used as the baseline concentrations for the NF treatments. For each NF treatment (NF-1, NF-2, N-3, and NF-4) a different but constant amount of O_3 (approximately 0.005, 0.019, 0.032, and 0.051 $\mu L\ L^{-1}$, respectively, above ambient O_3) was added for 7-h d^{-1} (1000–1700 h EDT) producing a series of 7-h O_3 curves that followed the daily O_3 curve in ambient air. Dispensing of O_3 began on 9 June as the first foliar leaves expanded. Ozone was added daily until 5 October (119 d), when leaves of plants in all but the CF and NF-1 treatments were necrotic. However, O_3 was not added during periods of rain (38.5 exposure h during the season) or when dispensing systems malfunctioned (52.5 exposure h during the season).

The four levels of SO_2 consisted of exposure to CF air with no added SO_2 (S-0) or NF ambient air to which approximately 0.020, 0.097, or 0.350 $\mu L\ L^{-1}$ of SO_2 (S-1, S-2, and S-3) was added for 4 h d^{-1} (1000–1400 h EDT). Sulfur dioxide was dispensed from 11 June to 5 October except during periods of rain (24.5 exposure h during the season) or system malfunction (8.8 exposure h during the season).

Five plots were randomly assigned to chambers equipped with a frustum that increased chamber height by 0.5 m and decreased the chamber open-top diameter from 3.0 to 2.1 m. These were used to expose plants to the five O_3 treatments with no SO_2 added. Results from these chambers were compared to results from the same treatments in chambers without frusta (regular chambers).

For response measures, each treatment plot was subdivided into two 1-m sections in each of two rows with approximately 40 cm at the ends of each row used only as border. Foliar injury was visually estimated as the combined percentage chlorosis and necrosis in 5% increments (0–100%) for all individual leaves arising from the main stem of four plants (one randomly chosen for each 1 m of row) per plot. Abscised leaves were rated as 100% injured. Injury estimates and square and boll counts were made on 16 July, 24 August, and 24 September using the same plants on all dates.

Seed cotton from the treatment plots was handpicked from each 1-m section of row and weighed on 28 September and on 5, 12, 20, and 27 October. Seed cotton from the companion plots was picked and weighed on 28 September and on 5, 15, 20, and 28 October. To simulate mechanical harvest, only fluffy locks were picked. At the final harvest, the number and weight of unopened bolls and of bolls that were open but not harvestable (immature) were determined. The shoots (stems, branches, and locules) were dried for 30 d in a greenhouse and weighed. A 500-g sample of seed cotton from the pooled harvest of each plot was ginned, and the percentages of lint and seed weight were determined. Standard market quality analyses were performed for lint (one sample per plot) at the USDA Agricultural Marketing Service, Cotton Testing

Laboratory at Clemson, SC, and for seed (one sample per plot) at Hahn Lab., Columbia, SC. Because the mean percentages of fiber and seed varied by <1% for all treatments, seed cotton was used as the measure of yield for all subsequent discussions.

Statistical Analyses

The analysis of data involved several steps. First, yield data (whole plot means) from the companion plots were analyzed to determine the nature of variation within the field. The companion plot yield data and the field coordinates of the companion plots were used to determine a polynomial response surface for the field. The predicted response surface values for each treatment plot and the average companion plot values (mean of the two nearest companion plots) for each treatment plot were computed as possible covariates.

Second, an analysis of variance was performed to test the effects of chamber quadrant (1-m row sections) positions within treatment plots. The experimental design allowed no true estimate of pure error. Thus, the significance of main effects and interactions of O_3, SO_2, and the frustum top were tested when the response surface models were fit. Injury proportions were subjected to arcsin transformation, which successfully stabilized variances among treatments. The key findings for both yield and injury data were that quadrant effects were significant as tested against the treatment by quadrant interaction mean square. Yield of plants in the southwest quadrant was 10 to 16% less than that for the other three quadrants. However, the treatment by quadrant interaction mean square (1858) was almost identical to the residual mean square from the response surface model (1880), which had been multiplied by 4 to adjust it to the quadrant level. This evidence suggested that the chamber effect (quadrant effect) did not affect plant response to O_3. Examination of the quadrant by treatment means showed that yield in the southwest quadrant was decreased by 54% in the highest O_3 treatment (compared to the CF treatment) while the mean decrease in the other three quadrants was 51%. Therefore, subsequent analyses involved the mean over the four quadrants of the treatment plots. Analyses of the means were used to assess the importance of the covariate data obtained from the companion plots. Neither the fitted values nor the averaged values of the companion plot data accounted for a significant part of the field variation. Consequently, the final dose-response models were fit without covariates.

The fourth phase of the analysis involved fitting polynomial dose-response models including both O_3, SO_2, and frustum effects. The seasonal 7- or 4-h mean concentrations of O_3 and SO_2, respectively, [shown in Table 1] were used as values for the independent variables. A dummy variable was used to indicate the presence and absence of the frustum. The appropriate response surface model was determined using Mallows *Cp* statistic (5) as the criterion. The residual mean square from that response surface model was used as the estimate of experimental error for all tests of significance and in calculating the standard errors of the regression coefficients. In all cases, the significance of a particular polynomial term mandated that all lower-order terms contained in that model be retained.

The bivariate Weibull response model (16) was also used to characterize the O_3-SO_2-frustum response surfaces. The deviations of the mean squares from this model were compared to the above estimate of experimental error for a judgement of the adequacy of the Weibull model.

RESULTS

The mean 7 h d^{-1} O_3 concentration during the period of dispensing (seasonal 7-h mean) in ambient air (AA) was 0.053 $\mu L\ L^{-1}$. The seasonal 7-h means for the O_3 treatments in regular and frustum chambers and the mean seasonal 4 h d^{-1} concentrations (4-h means) for the SO_2 treatments are shown in Table 1. The frusta decreased ingress of ambient O_3 by 50% as shown by seasonal 7-h mean concentrations in frustum CF chambers (0.013 $\mu L\ L^{-1}$) and regular CF chambers (0.026 $\mu L\ L^{-1}$). The number

Table 1. Ozone and SO_2 concentrations for studies to determine the effects of daily exposures on Stoneville 213 cotton.

Seasonal 7-h d^{-1} mean O_3 concentration†			Seasonal 4-h d^{-1} mean SO_2 concentration	
Treatment	Regular chambers	Chambers with a frustum	Treatment	Regular chambers
	$\mu L\ L^{-1}$			$\mu L\ L^{-1}$
CV	0.026	0.013	S-0	0.000
NF-1	0.058	0.058	S-1	0.020
NF-2	0.072	0.067	S-2	0.097
NF-3	0.085	0.087	S-3	0.350
NF-4	0.104	0.095		
AA	0.053		AA	0.000

† Means for the period from 9 June to 5 Oct. 1982 (1000–1700 h EDT). Each value for regular chambers is the mean for four chambers. Each frustum chamber value is the value for one chamber.
‡ Means for the period from 11 June to 5 Oct. 1982 (1000–1400 h EDT) excluding values for hours with no SO_2 dispensing. Each value is the mean for five chambers.

and seasonal timing of relatively high or low daily O_3 concentrations is shown by the daily 7- and 24-h AA means in Fig. 1. Daily 7-h mean O_3 concentrations for the NF-1, NF-2, NF-3, and NF-4 treatments can be estimated by adding 0.005, 0.019, 0.032, or 0.051 $\mu L\ L^{-1}$, respectively, to the 7-h values in Fig. 1. The mean seasonal diurnal patterns in O_3 concentration for AA and for the chamber treatments for the period from 9 June to 5 October are shown in Fig. 2.

Although the amounts of SO_2 added to the fan box for each chamber treatment were constant throughout the season, variation in ambient wind velocity effectively created different concentrations within the chambers because of the dilution by ambient air ingress through the open tops. The fluctuations in daily 4-h means and mean seasonal 4-h curves are shown in Fig. 3 and 4, respectively.

Foliar Injury and Boll Development

Foliar injury, which included chlorosis, bronzing, senescence, and abscission, increased with increasing O_3

Table 2. Mean percentage of injury per leaf and mean number of bolls and squares per plant on Stoneville 213 cotton exposed to different doses of O_3 in open-top chambers with or without frusta.

Seasonal 7 h d^{-1} O_3 conc., $\mu L\ L^{-1}$	Mean percentage injury per leaf†			Mean no. of bolls and squares per plant†		
	16 July	24 Aug.	24 Sep.	16 July	24 Aug.	24 Sep.
		Regular chambers				
0.026	8	48	79	9	15	10
0.058	27	66	93	8	17	10
0.072	37	75	96	8	16	9
0.085	43	80	98	7	14	7
0.104	54	85	99	8	14	7
		Chambers with frusta				
0.013	17	40	87	9	17	12
0.058	24	58	79	8	20	12
0.067	37	75	94	8	14	8
0.087	44	83	91	11	10	7
0.095	48	82	99	6	13	6

† Each value for plants in regular chambers is the mean of 16 plants (four plants in each of four chambers; values combined across SO_2 levels). Each value for chambers with a frustum is the mean for four plants (one in each chamber quadrant) at the ambient SO_2 level.

Table 3. Effects of chronic doses of O_3 on number and weight of immature bolls, number of harvestable bolls, weight of seed cotton, and shoot weight.

Seasonal 7 h d^{-1} O_3, conc.	Immature bolls: No. m^{-2}	Immature bolls: Weight† per boll	Immature bolls: total weight m^{-2}	No. of harvested bolls m^{-2}	Seed† cotton wt per boll	Seed cotton wt m^{-2}	Locule, stem and branch wt m^{-2}	Total shoot wt m^{-2}
μL L^{-1}		g			g			
			Regular open-top chamber‡					
0.026	30	4.5	136	65	5.5	357	311	804
0.058	25	3.1	78	61	5.2	316	252	646
0.072	21	2.3	48	57	4.8	275	207	530
0.085	16	2.5	40	48	4.5	217	181	441
0.104	12	2.3	27	38	4.2	161	143	331
			Chambers with frusta§					
0.013	19	3.1	58	71	5.3	373	305	796
0.058	20	4.3	86	58	5.2	300	211	597
0.067	12	2.2	26	58	4.6	269	213	508
0.087	18	2.5	45	49	4.5	222	176	443
0.095	12	2.0	24	48	4.1	199	174	397

† These values were obtained by dividing the total weights by the number of bolls.
‡ Each value for plants in regular chambers is the mean of 16 rows, 1-m long each (four rows in each of four chambers – values combined across SO_2 levels). Values for weight of seed cotton per meter of row for the four SO_2 treatments (data combined across O_3 levels) were 264, 254, 275, and 268 g at 0.000, 0.020, 0.097, and 0.350 μL SO_2 L^{-1}, respectively.
§ Each value for plants in chambers with a frusta is the mean for four rows, 1-m long each (one row in eachchamber quadrant at the ambient SO_2 level).

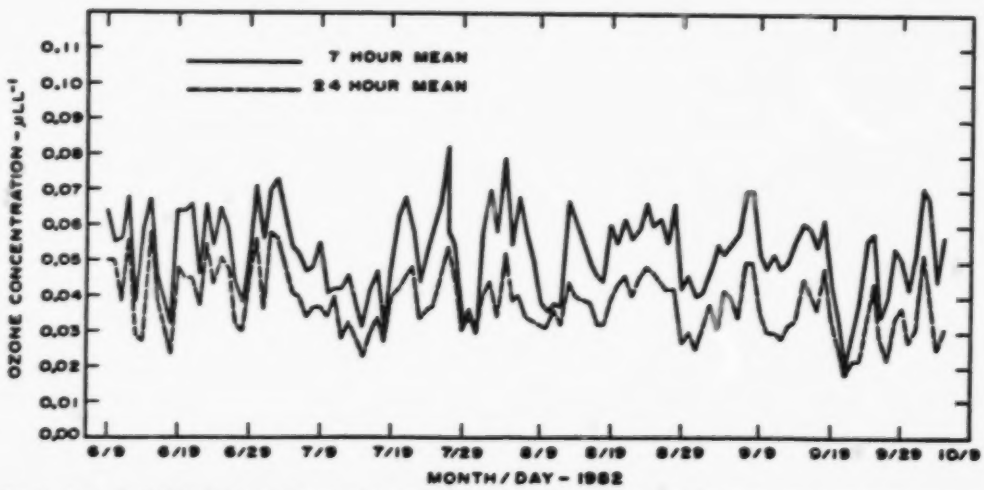

Fig. 1. Daily 7- (1000–1700 h EDT) and 24-h mean O_3 concentrations in ambient air during the period of exposures.

concentration and duration of exposure (Table 2). As indicated by regression analyses, there was no evidence that SO_2 caused foliar injury and no evidence that SO_2 changed the foliar injury response to O_3. Mean foliar injury (averaged across all O_3 levels) at each SO_2 level was almost identical (±2% of the overall mean) at each treatment date (data not shown). By 24 September, mean foliar injury was >90% for all NF treatments in the regular chambers and in all NF treatments except the NF-1 treatment in frustum chambers (Table 2). There was a trend toward fewer squares and bolls as the O_3 concentration increased at all harvest dates (Table 2) but the effects were statistically significant only on 24 September.

Cotton Yield

The regression analyses for number of harvested bolls and yield showed highly significant relationships for O_3 doses but no significant effects of SO_2, of interactions between O_3 and SO_2, or of interactions between O_3 and whether or not chambers had frusta. Thus, the means for the O_3 treatments averaged over SO_2 levels are shown in Table 3. The number and weight of immature bolls decreased with increased O_3 concentrations. The exceptions to this generality, seen in Table 3 for the frustum chambers, were probably due to results in the 0.013 and 0.067 μL L^{-1} treatments where values were lower than expected based on values observed in the regular chambers. We do not know whether this variation was random or caused by the frusta. Trends for number of harvested bolls, weight of seed cotton per boll, and yield were the same for both types of chambers (Table 3). For the regular chambers, yield at 0.058, 0.072, 0.085, and 0.104 μL L^{-1} was 11, 23, 39, and 55% less, respectively, than yield at 0.026 μL L^{-1} (Table 3).

The accumulative weights of seed cotton (yield) over the five harvests for the five O_3 treatments (SO_2 treatments combined) are shown in Fig. 5. At harvest one,

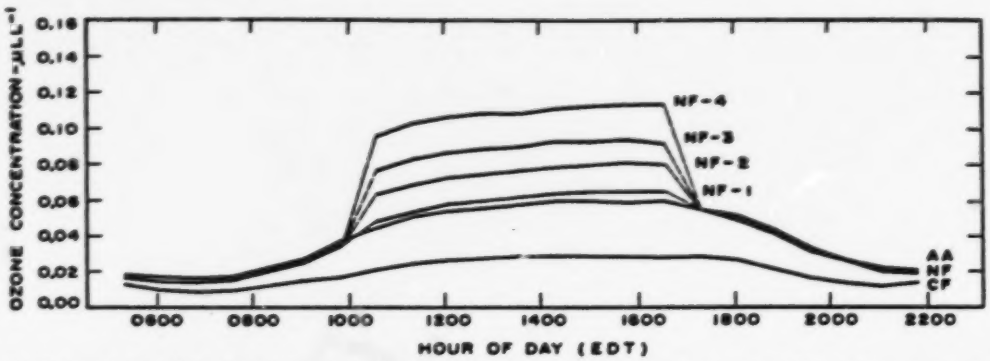

Fig. 2. Seasonal (9 June–5 Oct. 1982) diurnal fluctuation in concentration for the various O_3 treatments. CF = charcoal-filtered-air chamber; NF = the common concentration for all nonfiltered-air chambers during the period of each day when O_3 was not added; AA = ambient air; NF-1, -2, -3, and -4, = concentrations for nonfiltered-air chambers during the daily 7-h dispensing periods.

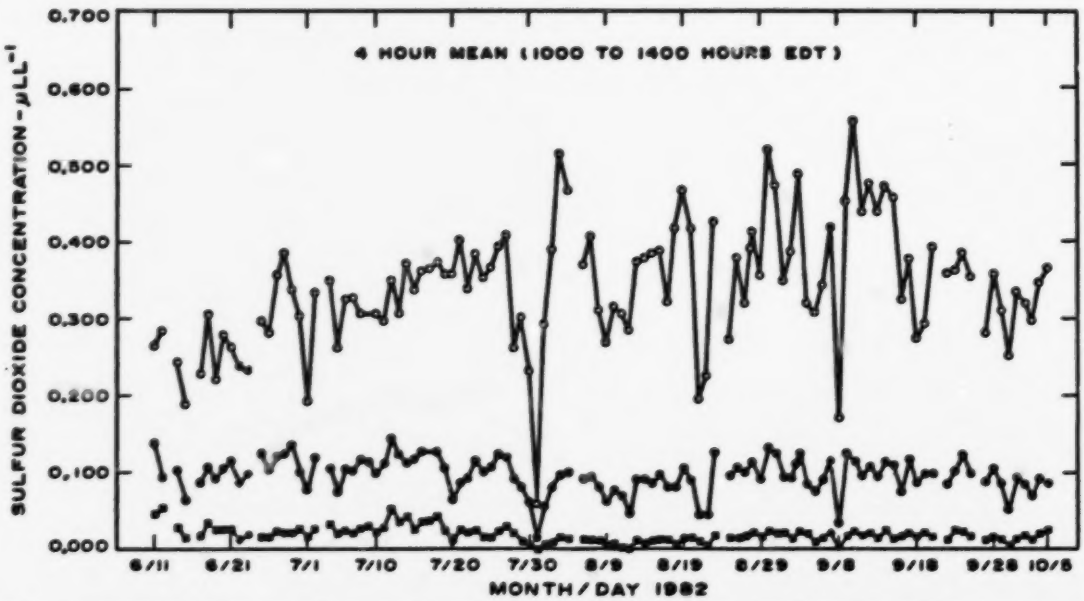

Fig. 3. Daily 4-h (1000–1400 h EDT) mean SO_2 concentrations for the S-1 (■–■), S-2 (●–●), and S-3 (O–O) treatments. * = values for days with <4 h of dispensing. Blanks indicate days where SO_2 was dispensed. Each value is the mean of five chambers.

yield was less in the high than in the low O_3 treatments. The yield increment from harvest one to harvest two was similar for all treatments but for later harvests, progressively less cotton was harvested in the high than in the low O_3 treatments.

The lack of significant interactions allowed us to capitalize on hidden replication with five replicates of each O_3 treatment (3). A quadratic polynomial model (Table 4) provided the best fit between seasonal 7 h d^{-1} mean O_3 concentrations and yield (Fig. 6). The fitting of the Weibull model (16) for yield and number of harvestable bolls showed no indication of any effect caused by SO_2 or the frusta. Therefore, the univariate Weibull model was fit to only O_3 levels averaged across SO_2 and frusta treatments to obtain a crop performance curve. The Weibull model and estimates of the Weibull parameters α, σ, and c for yield and number of harvested bolls are shown in Table 4. The estimated c values of 2.71

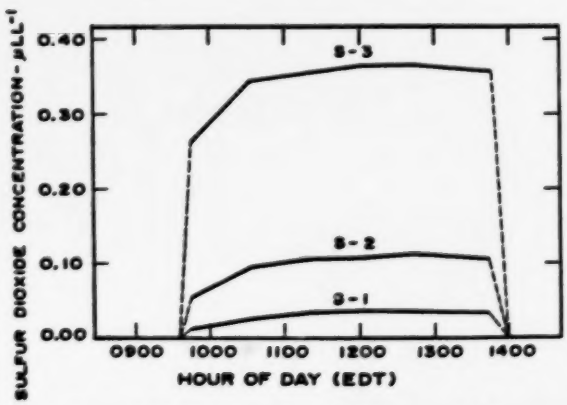

Fig. 4. Seasonal (11 June–5 October) 4-h fluctuation in SO_2 concentration for the S-1, S-2, and S-3 treatments.

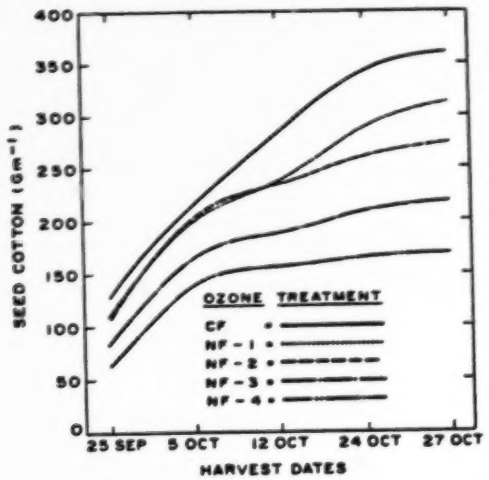

Fig. 5. Accumulative weight of seed cotton (g m^{-1}) from harvest one to harvest five for plants exposed to chronic doses of O_3. The curves were produced by computer-rounding to pass through coordinates for measured values (means across SO_2 treatments).

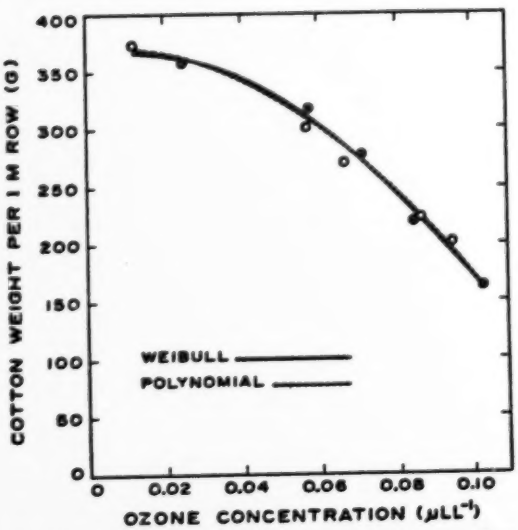

Fig. 6. Effects of O_3 on weight of seed cotton per meter of row as predicted by polynomial and Weibull analyses. ● = measured values in regular open-top chambers (each value is the mean of four plots of SO_2 levels combined). O = measured values in chambers with a frustum (each value is the mean of one plot).

for yield and 3.13 for boll number show a tendency toward a plateau effect, which was also shown in the polynomial model (Fig. 6).

Quality analyses for seeds showed that O_3 decreased seed size, percentage oil, and quality index (Table 5). Percentage moisture, free fatty acids in oil, and NH, were not significantly affected but lint quality was. As the O_3 concentration increased, fibers were shorter, less mature (lower micronaire values), brighter, and less yellow (Table 5). There were no trends suggesting effects on length uniformity or strength of fibers. The regression relationships for fiber length (upper-half mean length) and fiber maturity (micronaire) were significant and are shown as

Table 4. Polynomial and Weibull equations for yield and boll number of Stoneville 213 cotton exposed to chronic doses of O_3 and SO_2 in open-top field chambers.

	Polynomial†
Seed cotton wt per 1-m row	$Y = 372 + 54x - 20\,450\,x^2$ (21) (747) (5961)
Mean no. of bolls per 1-m row	$Y = 65.4 + 143x - 3876\,x^2$ (4.5) (157) (1249)
	Weibull‡
Seed cotton wt per 1-m row	$Y = 367 \exp[(-x/0.111)^{1.1}]$ (12) (0.003) (0.39)
Mean no. of bolls per 1-m row	$Y = 66.6 \exp[(-x/0.125)^{1.1}]$ (2.2) (0.007) (0.66)

† Y = predicted yield (weight of seed cotton) or number of bolls harvested per meter of row. Standard errors are shown in parentheses. There were no significant effects of SO_2 or the frusta on the O_3 response. Thus, SO_2 effects and frustum effects have been eliminated from the models. The chambers with and without frusta serve as effective replication of the O_3 treatments.

‡ For the Weibull model ($y = \alpha \exp[-x/\sigma]^c$; Y = estimated weight of seed cotton (g) per meter of row; x = O_3 dose as the seasonal 7 h d^{-1} mean concentration (μL L^{-1}); α = maximum seed cotton yield at 0 μL O_3 L^{-1}; σ = O_3 concentration at which α is reduced by 63%; and c is a dimensionless shape parameter. Standard errors in parenthesis are for α, σ, and c, respectively.

a footnote to Table 5. Regression analyses were not performed for other quality measures.

DISCUSSION

During the experimental period, daily 7-h mean O_3 concentrations in ambient air rarely exceeded 0.08 μL L^{-1} (Fig. 1), and no single daily exposure alone caused severe foliar injury. Rather, the succession of daily exposures progressively caused gradual foliar senescence and abscission. The rate of senescence depended on the O_3 treatment level and duration of exposure (Table 2). It is assumed that decreases in photosynthetic capability led to decreased growth rates and decreased weight of all vegetative and reproductive organs measured (Table 3).

The effects of a given O_3 dose on yield were intermediate to those found in 2 yr of tests with Acala SJ-2 cotton in California (18), where seasonal climate, seasonal exposure duration, and response to O_3 varied widely. In the California tests, a given seasonal 7 h d^{-1} mean O_3 concentration caused less of an effect in 1981, which was a warm and dry season, than in 1982, which was abnormally cool and humid. However, there were about half as many exposure days in 1981 as in1982. Thus, it is not known whether seasonal climate, exposure duration, or both, caused the differences. Both Acala SJ-2 and Stoneville 213 appear to be more sensitive to O_3-induced yield losses than many other crops tested (12, 13) but the relative sensitivity among cutlivars of cotton to yield loss from O_3 has not been tested.

We assume that the frustum decreased light intensity, wind turbulence (and therefore plant movement), and the amount of rain that entered the chambers although none of these factors was adequately measured. The frustum may also have affected temperature. Ingress of ambient air through the open tops caused fluctuations in O_3 concentrations that are directly dependent on several factors including wind velocity, wind velocity constancy, O_3 concentrations in ambient air, and the O_3 treatment within the chamber. For example, we have commonly observed on strip-chart recordings that such fluctuations are greater

Table 5. Effects of chronic doses of O_3 on cotton seed and lint quality factors.†

Seasonal 7 h d⁻¹ O_3 conc.	Seed: 100-seed wt	Seed: Oil	Seed: Quality index	Lint: HVI‡ upper half mean (inches)	Lint: Micronaire§	Lint: Color: Brightness	Lint: Color: Yellowness
μL L⁻¹	g	%				Rb-%	+b
Regular chambers							
0.026	10.2	20.0	109.4	1.11	4.9	76.8	9.2
0.058	9.9	19.2	106.6	1.08	4.6	78.0	9.4
0.072	9.9	18.7	103.9	1.09	4.3	78.8	8.8
0.085	9.4	17.6	101.5	1.09	4.2	79.0	8.4
0.104	8.9	16.8	97.6	1.07	3.8	80.0	8.8
Chambers with Frusta							
0.013	10.5	18.8	103.6	1.10	4.6	78.5	9.1
0.058	10.0	18.6	104.4	1.10	4.8	76.8	9.1
0.067	10.2	18.4	104.4	1.06	4.5	79.1	8.9
0.087	9.8	18.0	102.3	1.05	4.2	79.3	8.9
0.095	9.3	19.0	96.2	1.04	4.1	79.9	8.9

† Each value for plants in regular chambers is the mean of four samples (1 plot⁻¹). Each value for chambers with a frustum is for one sample. Descriptions of lint quality characteristics are contained in reference 20.

‡ The regression relationship and standard errors (in parentheses) between the O_3 concentration (x) and high volume instrument (HVI) upper half mean (Y = length in inches) was $Y = 1.11 - 0.450x$. (0.01) (0.181)

§ The regression relationship and standard errors (in parentheses) between the O_3 concentration (x) and micronaire (y) was $Y = 4.55 + 13.53x - 207.0x^2$. (0.20) (7.07) (56.4)

during gusty periods than during calm periods and greater in chambers with 0.05 μL O_3 L^{-1} added than in chambers with 0.02 μL O_3 L^{-1} added. During periods of high ambient O_3, wind caused O_3 concentrations to fluctuate in CF chambers and in NF chambers with O_3 added, but not in NF chambers with no O_3 added. Differences in the degree of fluctuation in O_3 concentrations was not measured but we assume that such fluctuations were much less in the frustum than in the regular chambers. Any effects of the frustum on chamber environment and exposure dynamics that occurred did not significantly affect the response of Stoneville 213 cotton to O_3 (Fig. 6). However, further studies are recommended to measure the effects of frusta on the chamber environment and to determine whether frusta affect response to O_3 for other important crop species.

Our main objective was to characterize a relative yield response of cotton to different levels of O_3 and SO_2. Thus, the mean level of cotton performance was not critical assuming a reasonable level of plant growth. While mean levels of crop performance are likely to vary greatly from season to season because of differences in soil moisture, temperature, and other climatic factors, there is good evidence that the relative response to a pollutant will remain fairly stable when climate does not vary widely. For example, the relative yield response of Davis soybean to O_3 at our site was the same in 1982 (10) as in 1981 (9). It was possible to fit a combined dose-response model for different soybean cultivars tested at different locations and in different seasons (12). As in the present study, we routinely find significant chamber position effects on growth and yield, but such effects have never been shown to significantly change plant response to O_3 (9, 10). The present study was performed during a relatively normal growing season with irrigation to prevent soil-moisture stress. While we would expect some variance in the relative yield response of Stoneville 213 to O_3 over years, we believe it would be minor with our present experimental protocols.

The lack of significant effects of SO_2 on Stoneville 213 cotton either singly or in combination with O_3 suggests that SO_2 is not a major factor in cotton production although it could be a factor near point sources of SO_2. Further studies should be performed to determine whether this is true for other cotton cutlivars and other crops.

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Characterization of Cadmium and Zinc in Four Soils Treated with Sewage Sludge[1]

G. L. MULLINS AND L. E. SOMMERS[2]

ABSTRACT

Cadmium and Zn were characterized in soils treated with 100 Mg ha^{-1} of an anaerobically digested sewage sludge from Chicago, IL. The four soils included a Chalmers silt loam (Typic Haplaquolls) (Indiana), Celina loam (Aquic Hapludalfs) (Michigan), Celina silt loam (Aquic Hapludalfs) (Ohio), and a Plano silt loam (Typic Aquidolls) (Wisconsin). The single application of sludge supplied 19 kg Cd ha^{-1} and 340 kg Zn ha^{-1}. Four or five crops of barley (*Hordeum vulgare* L.) had been grown on each site prior to soil sampling. Soil solutions obtained by a centrifugation method contained Zn in the range of 1.4 to 10.5 μmol L^{-1} while Cd ranged from 18 to 135 nmol L^{-1}. The addition of sludge increased the concentration of both metals in the soil solutions of all four soils. Evaluation of soil solution data with the computer program GEOCHEM showed that >85% of the total soluble Cd and >91% of the total soluble Zn existed as the free metal ion. Sludge addition increased the amount of Cd and Zn extracted by DTPA and 4 *M* HNO_3. The relative increases in soil solution and extractable Cd and Zn were different in each of the four soils even though the same sludge was applied at the same rate. Diffusion coefficients measured with a cation exchange resin paper method (D_e), ranged from 1.8×10^{-11} to 1.7×10^{-9} cm^2 s^{-1} for Zn and from 5.2×10^{-11} to 3.2×10^{-10} cm^2 s^{-1} for Cd. The application of sludge had little or no effect on the magnitude of D_e for either Cd or Zn as measured by the resin paper method, but the diffusion coefficients for Zn were inversely related to soil pH. Increases in the flux of Cd and Zn to plant roots in sludge-treated soils will be a reflection of changes in soluble and extractable Cd and Zn.

Additional Index Words: **soil solution, diffusion, diffusion coefficients, extractable metals, GEOCHEM, isotopic exchange.**

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Plant uptake of Cd and Zn can be increased by applying sewage sludge to agricultural soils (Page, 1974). Since Cd and Zn reach plant roots by the processes of root interception, mass flow, and diffusion (Barber et al., 1963), one or more of these trace element transport processes are altered by applying sludges to soils. The application of sewage sludge to soils will probably influence all three mechanisms for supply of Cd and Zn to roots. Sewage sludge applications increase the concentration of Cd and Zn in the soil solution (Behel et al., 1983). Sludge applications also increase soil Cd and Zn extracted by DTPA (Kelling et al., 1977) and 0.1 *M* HCl (Hinesly et al., 1977). Increases in the soluble and extractable metal fractions should increase the amount supplied by root interception, mass flow, and diffusion. Warncke and Barber (1972a, b) showed that the effective diffusion coefficients for Zn in five soils depended on volumetric moisture and soil bulk density. The effect of sludge additions on effective diffusion coefficients of Cd and Zn in soils has not been adequately characterized.

The amount of an ion that reaches plant roots by mass flow will depend on the concentration in the soil solution and the flux of water to the root. Diffusion will become important when the root system is absorbing ions faster than they can be supplied by mass flow and root interception, resulting in establishment of a concentration gradient around the root. The amount of an ion supplied by diffusion will depend on the concentration gradient and the magnitude of the diffusion coefficient. Oliver and Barber (1966) and Wilkinson et al. (1968) have shown that diffusion is the most important process in supplying Zn to plant roots.

The objectives of this study were to determine the changes in soil solution Cd and Zn, labile soil Cd and Zn, and Cd and Zn diffusion coefficients as a result of sludge application.

MATERIALS AND METHODS

Four soils located in Indiana, Michigan, Ohio, and Wisconsin (Table 1) were treated in 1978 with 100 Mg ha^{-1} of an anaerobically digested sewage sludge from Chicago, IL. A total of 19 kg Cd ha^{-1} and 340 kg Zn ha^{-1} was applied to each soil by the single application of sludge. A composite soil sample was obtained by sampling the Ap horizon of four replicates of untreated and sludge-treated soils in August 1982. Four or five crops of barley (*Hordeum vulgare* L.) had been grown on each site prior to sampling. The samples were air-dried, ground to pass a 2-mm stainless steel screen, and stored in polyethylene lined containers.

Soil Characterization Methods

Soil pH was determined with a glass electrode using a 1:1 soil/water ratio and a 30-min equilibration period. Particle size distribution of the untreated soil was determined with a pipette procedure (Franzmeier et al., 1977). Total soil C was measured with a Leco C analyzer (Nelson and Sommers, 1982) and total N by the method of Nelson and Sommers (1972). Cation exchange capacity (CEC) was determined by summing extractable cations and H^+. Cations were extracted with 1 *M* NH_4OAc and determined by atomic

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[2]Former Research Assistant, Agronomy Dep., Purdue Univ., now Assistant Professor of Agronomy, Dep. of Agron. and Soils, Auburn Univ., AL 36849-4201; and Professor, Agronomy Dep., Purdue Univ., now Professor and Head, Dep. of Agronomy, Colorado State Univ., Fort Collins, CO 80523.